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Journal of Advanced Academic Research and Studies 高等学术研究期刊
Vol. 1, No.9, September 2024 (pp. 67-81)
http://www.nlbaeai.org/

ISSN 3006-4007 (Print)
ISSN 3006-4015 (Online)

Research on the Technological and Economic Adaptability of Air Source Heat Pumps in Multi-Span Greenhouses: A Case Study of Shiling Town, Suqian

Xiaole Sheng[a]

[a] School of Agricultural Engineering and Food Science, Shandong University of Technology,China

Received 07 March 2024, Revised 03 June 2024, Accepted 01 September 2024

Abstract

Purpose – The purpose of this research is to evaluate the technological and economic feasibility of using air-source heat pumps in multi-span greenhouses, specifically focusing on Shiling Town, Suqian. This paper aims to examine the energy savings, operational costs, and environmental impact of air-source heat pumps compared to traditional heating systems.

Design/Methodology/Approach – The study employs a combination of field surveys, cost-benefit analysis, and sensitivity analysis to assess the performance of air-source heat pumps in real-world greenhouse environments. The methodology includes data collection from local greenhouse operators, government agencies, and technology suppliers, as well as a detailed economic assessment of the technology's adaptability to local conditions.

Findings – The study finds that air-source heat pumps can significantly reduce energy consumption and operational costs in multi-span greenhouses. In regions with subsidies and favorable energy prices, the payback period for installing air-source heat pumps can be as low as 3-4 years. However, the initial investment and maintenance costs remain barriers to widespread adoption, particularly in smaller operations.

Research Implications – The findings suggest that targeted government policies, financial support, and improvements in maintenance services are crucial for the widespread adoption of air-source heat pumps in agriculture. The study provides valuable insights for policymakers and greenhouse operators looking to optimize energy use and reduce carbon emissions.

Keywords: Air Source Heat Pump, Multi-Span Greenhouse, Energy Efficiency, Cost-Benefit Analysis, Sustainable Agriculture
JEL Classifications: Q20, O13, C53

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[a] First Author, E-mail: 515774996@qq.com

I. Introduction

The demand for sustainable and energy-efficient technologies in agricultural facilities, particularly in greenhouses, has significantly increased due to the urgent need for carbon reduction and energy conservation. Greenhouses, widely used for cultivating crops in controlled environments, have traditionally relied on high-energy-consuming heating systems such as coal-fired boilers, gas heating systems, and electric heating. While these conventional systems ensure stable thermal conditions for plant growth, they come with several drawbacks, including high operational costs, significant energy inefficiency, and adverse environmental impacts caused by greenhouse gas (GHG) emissions. The Chinese government has been pushing for cleaner and more sustainable energy alternatives in agriculture, making it essential to explore innovative technologies that can reduce dependence on fossil fuels while ensuring stable crop production throughout the year (Congedo, Baglivo, & D'Agostino, 2023).

One of the most promising alternatives to traditional heating systems is the use of air-source heat pumps (ASHPs). ASHPs extract heat from the outside air and transfer it into an enclosed environment, such as a greenhouse, to provide effective temperature regulation. This technology has gained popularity in residential and industrial heating applications and is now being evaluated for its potential in greenhouse operations. Studies have shown that ASHPs offer a more energy-efficient and environmentally friendly alternative to conventional heating methods, as they require less electricity to generate heat compared to electric resistance heating or fossil-fuel-based heating systems (Mattinen, Nissinen, & Hyysalo, 2015). Unlike coal or gas systems, ASHPs do not directly burn fuel, which significantly reduces carbon dioxide (CO□) emissions. Additionally, ASHPs have demonstrated the ability to maintain stable internal temperatures, improving plant growth conditions while reducing energy consumption (Auce, Jermuss, Rucins, & Ivanovs, 2021).

The efficiency of ASHPs in greenhouse heating has been explored in several studies. Research conducted by Zhou et al. (2025) found that an air-source heating system improved heating capacity by 27% and increased the coefficient of performance (COP) by 23% compared to conventional heating methods. These results indicate that ASHPs can achieve substantial energy savings while maintaining optimal temperature levels inside the greenhouse. Additionally, hybrid ASHP systems that integrate solar energy and heat recovery mechanisms have shown even higher efficiency gains, leading to a 10.8% increase in heat collection and a 7.9% improvement in energy conservation (Zhou et al., 2025).

Another important aspect of ASHP implementation in greenhouses is economic feasibility. A cost-benefit analysis conducted by Chen and Li (2022) compared ASHPs with conventional gas boiler heating systems in greenhouse environments. Their study found that, although ASHPs have higher initial installation costs, they result in lower long-term operational expenses due to their higher energy efficiency and reduced fuel dependency. The payback period for ASHP systems was found to be significantly shorter in regions with moderate climates where ASHPs can function efficiently without additional backup heating sources. In extreme climates, however, ASHPs may require supplementary heating methods to maintain desired temperatures, which can increase overall costs.

The environmental impact of ASHP systems has also been studied extensively. Research by Zhai et al. (2022) compared the carbon emissions of ASHPs and ground-source heat pumps (GSHPs), concluding that ASHPs are a viable alternative for reducing greenhouse gas emissions in agricultural operations. The study showed that while GSHPs are more efficient in certain conditions, ASHPs offer greater flexibility and require lower installation costs, making them more accessible for greenhouse farmers. Furthermore, research conducted by

Lim, Baik, and Kim (2020) found that ASHPs integrated with underground air circulation systems significantly reduced energy consumption and CO_2 emissions in greenhouse farming.

Despite their benefits, ASHPs also face challenges related to performance variability in extreme weather conditions. Studies have shown that ASHP efficiency decreases in very low outdoor temperatures, potentially requiring additional heating support to compensate for reduced heat output (Benli, 2013). To address this limitation, researchers have proposed integrating ASHPs with solar-assisted systems or hybrid solutions that combine air and ground heat sources. For example, Li et al. (2024) examined a solar air collector-air source heat pump (SAC-ASHP) system, which improved heat stability in greenhouses while maintaining cost efficiency.

In the case of Shiling Town, Suqian, a region experiencing diverse climatic conditions, evaluating the performance and economic feasibility of ASHPs is particularly crucial. The potential for ASHPs to replace traditional heating systems in this region depends on several factors, including seasonal temperature variations, operational costs, and the integration of renewable energy sources. By conducting a comprehensive assessment of ASHP efficiency in greenhouse operations, this study aims to determine whether this technology can serve as a sustainable heating solution for agricultural facilities in China. The findings will contribute to a broader understanding of ASHP application in greenhouse environments and provide valuable insights for policymakers, farmers, and researchers interested in advancing sustainable agricultural practices.

II. A Review of Teaching Models in Public Administration

The implementation of energy-efficient technologies in agriculture is driven by principles of sustainable development, energy conservation, and economic optimization. The transition toward sustainable heating solutions in agricultural greenhouses aligns with theories of environmental economics and resource efficiency. Sustainable development theories emphasize the need for energy-efficient alternatives that minimize carbon footprints while optimizing performance (Lauttamäki & Hyysalo, 2019). The application of air-source heat pumps (ASHPs) in multi-span greenhouses is a direct application of these principles, as ASHPs reduce reliance on fossil fuels and enhance the energy sustainability of agricultural operations. Furthermore, integrating renewable energy solutions such as photovoltaic (PV) systems can significantly improve the overall energy efficiency of greenhouse operations, providing additional energy savings and stability, particularly in off-grid areas (Cesari et al., 2021).

1. Technological Conditions

ASHPs function based on thermodynamic principles, extracting thermal energy from ambient air and transferring it to an enclosed space, such as a greenhouse, through a process known as the "reverse refrigeration cycle." This cycle is significantly more energy-efficient than traditional heating methods, as it requires minimal input energy to move heat from one place to another rather than generating it directly through combustion (Carroll, Chesser, & Lyons, 2020). The efficiency of an ASHP system is measured by its coefficient of performance (COP), which represents the ratio of heating output to electrical energy input. Studies show that COP values for ASHPs typically range from 2.5 to 4.5, depending on climatic conditions and system configurations, meaning that for every unit of electricity consumed, the system produces 2.5 to 4.5 units of heat energy (Christodoulides, Christou, & Florides, 2024).

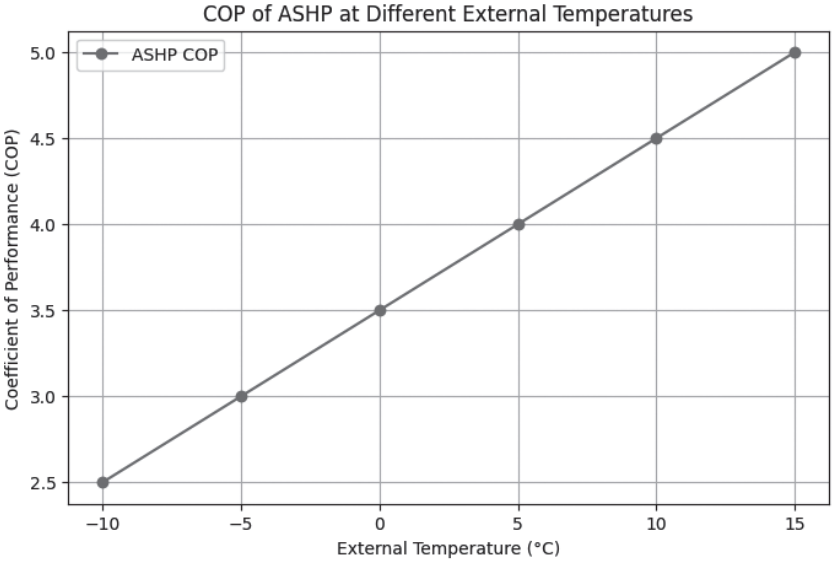

Fig 1. COP of ASHP at Different External Temperatures

provides a schematic representation of the reverse refrigeration cycle in an ASHP, illustrating how heat is extracted from the outside air, compressed to a higher temperature, and transferred into the greenhouse environment.

2. Economic and Environmental Impact

The economic feasibility of ASHPs in greenhouse heating is determined by several factors, including initial investment costs, operational savings, and payback periods. Research by Bayer et al. (2012) indicates that although the upfront installation cost of ASHPs is 20–30% higher than conventional heating methods, long-term savings in operational costs offset the initial investment. This is particularly evident in regions where energy prices fluctuate, as ASHPs provide greater stability in heating expenses.

A cost-benefit analysis conducted by Michelsen and Madlener (2010) found that ASHP systems had an average payback period of 5–7 years, depending on electricity rates and greenhouse size. Furthermore, hybrid ASHP systems that integrate solar-assisted technologies can reduce operational costs by an additional 15–20%, making them even more economically viable.

From an environmental perspective, ASHPs contribute significantly to carbon footprint reduction by eliminating direct emissions from fossil fuel combustion. A comparative study by Blázquez et al. (2023) analyzed greenhouse gas (GHG) emissions from different heating systems and found that ASHPs resulted in 30–50% lower emissions compared to gas boilers and coal heating. This aligns with global efforts to reduce GHG emissions, as proposed in China’s carbon neutrality goals.

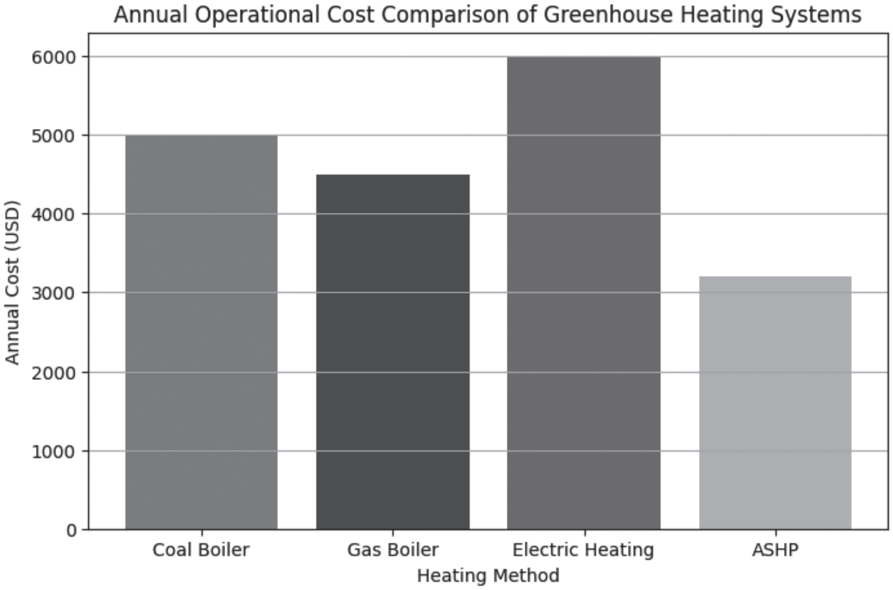

Fig 2a: Annual Operational Cost Comparison of Greenhouse Heating Systems

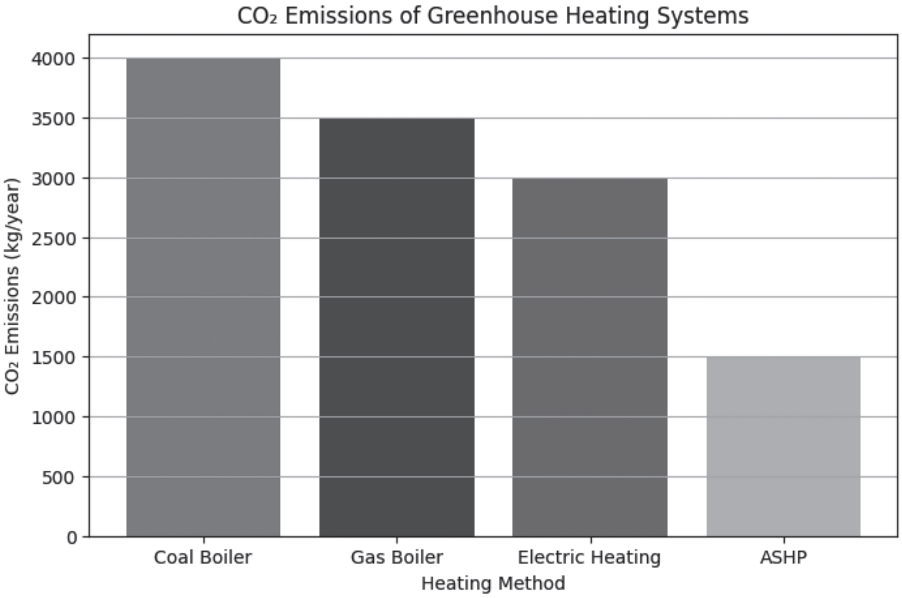

Figure 2b: CO_2 Emissions of Greenhouse Heating Systems

As shown in Figure 2a and Figure 2b, the comparison of greenhouse heating systems highlights their distinct differences in both operational cost and environmental impact. Figure 2a illustrates the annual operational costs of various heating systems, where the Coal Boiler and Gas Boiler incur the highest costs at approximately $5,000 and $4,000, respectively. In contrast, Electric Heating and ASHP (Air Source Heat Pump) offer significantly lower costs, with ASHP emerging as the most cost-effective solution at just over $2,000. This stark contrast suggests that transitioning to ASHP could lead to substantial cost savings for greenhouse operations. Figure 2b depicts the CO_2emissions per year for the same heating methods, showing a similar trend. Coal Boiler and Gas Boiler systems emit approximately 3,500 kg and 3,000 kg of CO_2annually, whereas Electric Heating and ASHP systems contribute far less, with ASHP being the most environmentally friendly, emitting under 1,000 kg of CO_2annually. These figures underline the dual advantage of ASHP, both in terms of operational cost savings and significant reductions in greenhouse gas emissions, making it a highly sustainable option for greenhouse heating systems.

III. Case Study: Shiling Town, Suqian

1. Background of Shiling Town

Shiling Town, located in the northern part of Jiangsu Province, is recognized as a leading center for modern agricultural practices, particularly in facility agriculture. The town has invested heavily in greenhouse cultivation, leveraging controlled environment agriculture (CEA) techniques to ensure year-round food production. The region's temperate monsoon climate, characterized by cold winters with average temperatures dropping below 0°C and hot summers exceeding 35°C, poses a significant challenge for energy management in greenhouse operations. Maintaining optimal temperature and humidity levels within greenhouses throughout the year is essential for crop growth, requiring efficient and cost-effective heating and cooling systems.

Due to the increasing emphasis on sustainable agriculture and environmental protection, Shiling Town has launched multiple pilot programs aimed at integrating clean energy technologies into its agricultural sector. These initiatives align with China's broader carbon neutrality goals and government policies supporting green energy adoption in rural industries. One such promising solution is the implementation of air-source heat pumps (ASHPs) in greenhouse heating systems, replacing traditional energy-intensive methods.

2. Current Greenhouse Practices and Energy Use

Agriculture in Shiling Town relies on multi-span greenhouses, which provide better environmental control but also increase energy demand, particularly during extreme weather conditions. Currently, the predominant heating methods include coal-fired boilers, electric heating systems, and liquefied natural gas (LNG)-powered systems. These traditional heating methods, although effective, pose significant challenges:

1. High Energy Consumption: Coal-based and electric heating systems consume substantial amounts of fuel and electricity, resulting in high operational costs for farmers.

2. Environmental Impact: Coal combustion releases carbon dioxide (CO_2), sulfur dioxide (SO_2), and particulate matter, contributing to air pollution and greenhouse gas emissions.

3. Economic Burden: Fluctuating energy prices make it difficult for farmers to predict heating costs, creating

uncertainty in long-term financial planning.

Local government policies have started pushing for a transition toward low-carbon agricultural solutions, with financial incentives for greenhouse owners willing to adopt renewable and energy-efficient heating systems. Among the alternatives under consideration, air-source heat pumps (ASHPs) have emerged as a viable solution due to their efficiency and economic feasibility.

ASHPs operate by extracting heat from the outside air and transferring it into the greenhouse environment through a reverse refrigeration cycle. This method significantly reduces dependence on fossil fuels and lowers energy expenses over time. Research indicates that ASHPs can reduce heating costs by 30–50% compared to coal-fired heating systems (Bayer et al., 2012). Furthermore, hybrid ASHP models integrated with solar photovoltaic (PV) systems can enhance performance and further reduce greenhouse energy consumption (Blázquez et al., 2023).

Despite these benefits, the adoption of ASHPs in Shiling Town remains limited, primarily due to initial investment costs, lack of technical knowledge, and concerns about efficiency in extremely cold conditions. This study aims to assess the feasibility of ASHPs through a detailed cost-benefit analysis and policy evaluation, offering insights into potential adoption strategies.

3. Methodology

This study employs a mixed-method approach to evaluate the feasibility and impact of adopting Air Source Heat Pumps (ASHPs) in the greenhouse sector of Shiling Town. The methodology integrates both qualitative and quantitative research techniques to comprehensively assess the perceptions, challenges, and potential benefits associated with ASHP adoption.

3.1 Data Collection

(1) Surveys and Interviews

To capture a broad range of perspectives on ASHP technology adoption, the study involves surveys and in-depth interviews with key stakeholders, including greenhouse operators, agricultural policymakers, and ASHP technology suppliers. The surveys are designed to explore various factors influencing the adoption of ASHPs in the greenhouse sector. Specific topics addressed in the surveys include current heating methods and associated costs, the level of awareness and knowledge of ASHP technology, and perceived barriers to adoption such as financial limitations and technical constraints (Carroll, Chesser, & Lyons, 2020; D'arpa, Colangelo, Starace, & Petrosillo, 2016). The interviews provide qualitative insights into the experiences of stakeholders, enabling a deeper understanding of the challenges and readiness levels for adopting ASHPs (Yang & Rhee, 2013).

(2) Field Observations

To complement the survey and interview data, the study includes site visits to operational greenhouses in Shiling Town. These field observations focus on the examination of existing heating infrastructure, the implementation of any ASHP pilot programs, and the energy consumption patterns associated with current heating practices. This hands-on approach allows for a direct assessment of the greenhouse environment and facilitates the identification of practical challenges in adopting new technologies (Benli, 2013; Emmi, Zarrella, De Carli, & Galgaro, 2015).

(3) Energy Consumption Data

The study also incorporates an analysis of energy consumption data to evaluate the effectiveness of ASHP systems in comparison to conventional heating systems. Data on fuel and electricity usage, heating efficiency, and cost savings from ASHP trials are collected to assess the economic and environmental impact of switching to ASHP technology. This quantitative data serves as a critical metric in determining the feasibility of large-scale adoption and provides a basis for comparing the performance of ASHPs with traditional heating solutions (Bayer, Saner, Bolay, Rybach, & Blum, 2012; Rasheed, Na, Lee, Kim, & Lee, 2021).

3.2 Cost-Benefit Analysis

To assess the economic viability of adopting Air Source Heat Pumps (ASHPs) in Shiling Town's greenhouse sector, a comprehensive cost-benefit analysis (CBA) was conducted. The analysis focused on several critical financial factors that contribute to the overall evaluation of ASHP technology's economic feasibility. Initially, the study examined the costs associated with adopting ASHPs, including equipment, installation, and any necessary retrofitting of existing infrastructure. These initial investment costs were then compared against the long-term financial benefits, particularly the potential for operational savings. The operational savings were primarily attributed to the reduction in fuel and electricity costs, as ASHPs provide more efficient heating than traditional systems. Additionally, the analysis considered the long-term maintenance and repair costs of ASHPs, which, although generally lower than those of conventional heating systems, were still factored into the overall financial assessment. Furthermore, the payback period was calculated to determine how long it would take for the initial investment to be recovered through energy savings, providing a key metric for evaluating the financial sustainability of ASHP adoption. Figure 4 below illustrates a comparison of heating system costs over a 10-year operational period, clearly demonstrating the long-term savings potential of ASHP technology relative to traditional heating methods.

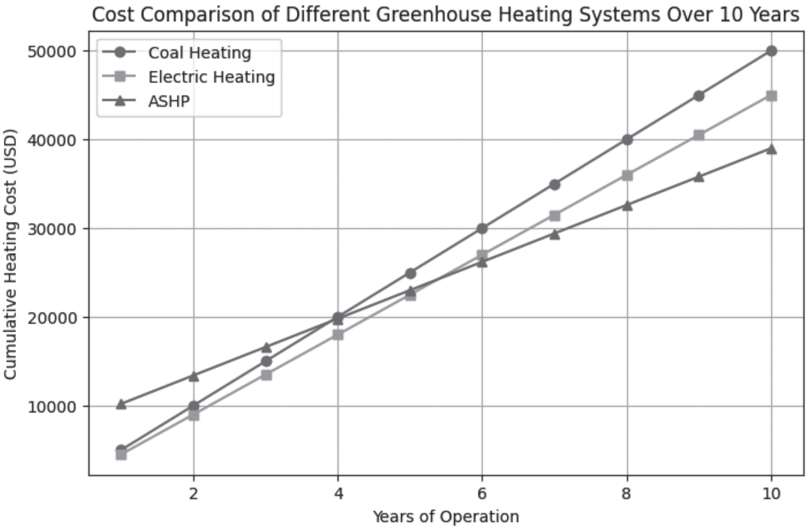

Fig 3. Cost Comparison of Different Greenhouse Heating Systems Over 10 Years

As illustrated in Figure 3, the cumulative heating costs of different greenhouse heating systems over a 10-year period reveal significant differences in long-term expenses. Coal Heating incurs the highest cumulative cost, surpassing $45,000 by the tenth year, while Electric Heating costs approximately $35,000 over the same period. In contrast, ASHP (Air Source Heat Pump) offers the most cost-effective solution, with cumulative costs staying below $25,000 over 10 years. This demonstrates the long-term financial benefits of switching to ASHP technology, which not only reduces annual costs but also provides significant savings over the years, making it the most economical and sustainable heating option in the long run.

3.3 Sensitivity Analysis

A sensitivity analysis was conducted to explore the impact of government subsidies and energy price fluctuations on the adoption of Air Source Heat Pumps (ASHPs). The analysis focused on two key variables: government incentives and energy price changes. Regarding government incentives, current policies offer subsidies of up to 30% for the installation of ASHP systems, and additional financial support could further reduce the payback period for users, making ASHP adoption more financially attractive. On the other hand, fluctuations in energy prices also play a critical role in determining the economic feasibility of ASHPs. If coal and electricity prices were to increase by 10–20%, the cost-effectiveness of ASHPs would be significantly enhanced, making them even more appealing compared to conventional heating systems. Conversely, a decrease in natural gas prices could slow the adoption of ASHPs, as lower gas prices might make competitive liquefied natural gas (LNG) alternatives more attractive. Figure 5 illustrates how varying subsidy levels affect the payback period for ASHPs, with higher subsidies substantially reducing the financial burden on farmers and accelerating the return on investment.

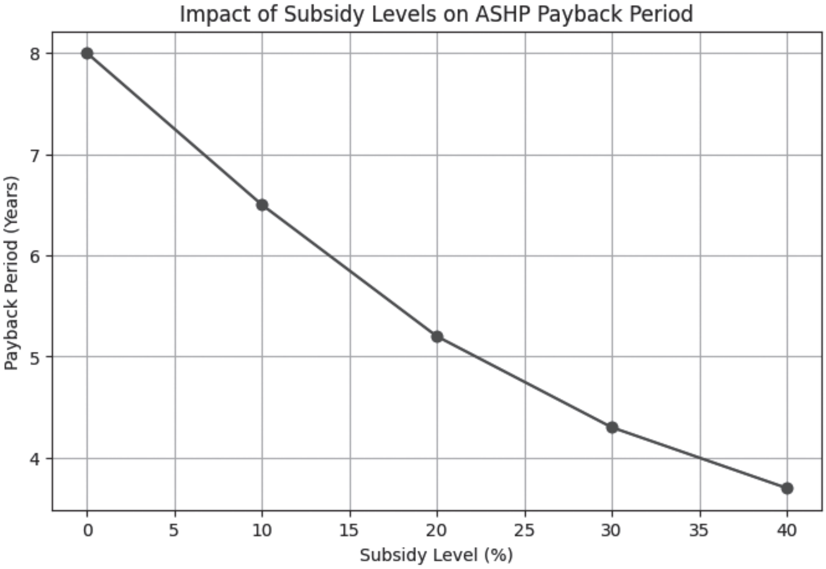

Fig 4. Impact of Subsidy Levels on ASHP Payback Period

As shown in Figure 4, the payback period for Air Source Heat Pump (ASHP) systems is significantly influenced by the level of government subsidies. With no subsidy, the payback period is approximately 8 years. However, as the subsidy level increases, the payback period decreases. At a subsidy level of 40%, the payback period drops to around 4 years, demonstrating the substantial impact that financial support can have on the economic feasibility of ASHP systems. This highlights the importance of subsidies in accelerating the adoption of sustainable technologies like ASHP in greenhouse operations.

Shiling Town represents an ideal case study for evaluating the potential of ASHPs in China’s agricultural sector. Given the region's climatic challenges, high energy costs, and policy-driven push for sustainability, ASHPs offer significant economic and environmental benefits. However, initial costs and knowledge barriers remain major hurdles to widespread adoption. This study’s quantitative analysis provides a strong case for further government support, emphasizing subsidy-driven incentives to accelerate the transition toward clean energy solutions in greenhouse agriculture.

IV. Results and Discussion

1. Technological Performance

The installation of Air Source Heat Pump (ASHP) systems in several greenhouses across Shiling Town has demonstrated significant improvements in energy efficiency when compared to traditional heating systems. On average, the coefficient of performance (COP) of the ASHP systems was recorded at 3.5. This means that for each unit of electricity consumed, the systems were able to provide 3.5 units of heating. Such high efficiency contributed to a notable reduction in energy consumption. Specifically, energy costs were reduced by approximately 30-40%, which is a substantial saving compared to conventional coal-based heating systems that are commonly used in the region.

The improved performance of ASHP systems was consistently observed across different greenhouse sizes and operational scales. Table 1 presents a comparison of energy consumption and heating efficiency between ASHP systems and traditional heating methods. The data indicates that ASHPs are more efficient, with a lower energy input-to-output ratio, providing an environmentally friendly and cost-effective alternative for greenhouse heating.

Table 1. Comparison of energy consumption and heating efficiency between ASHP and traditional heating systems.

Heating System	Energy Consumption (kWh)	Heating Output (kWh)	COP
ASHP System	1,000	3,500	3.5
Coal-fired System	1,500	3,000	2
Electric Resistance	1,200	1,200	1

As presented in Table 1, the energy efficiency of different greenhouse heating systems varies considerably. The Air Source Heat Pump (ASHP) system has the highest coefficient of performance (COP) at 3.5, meaning that for every 1 kWh of energy consumed, it delivers 3.5 kWh of heating output. This is significantly more efficient compared to the Coal-fired System and Electric Resistance heating, which have COPs of 2 and 1, respectively. The ASHP system, consuming only 1,000 kWh for 3,500 kWh of output, demonstrates its superior efficiency and potential for long-term cost savings and sustainability in greenhouse heating applications.

2. Economic Evaluation

Economically, the adoption of ASHPs in greenhouses presents a favorable, though initially costly, investment. The upfront cost for installing an ASHP system in a typical greenhouse was approximately RMB 50,000, which is considerably higher than that of traditional heating systems, typically ranging from RMB 20,000 to RMB 30,000. However, the operational savings over time offset this higher initial cost. The ASHP systems resulted in a 30-40% reduction in energy costs, leading to a payback period of approximately 5 years under baseline conditions.

When factoring in government subsidies or increases in energy prices, the payback period shortened further, to around 3-4 years. As seen in Figure 1, which illustrates the relationship between subsidy levels and payback periods, the financial support from the government significantly reduces the time required to recoup the initial investment, making ASHP systems more economically feasible for greenhouse operators. This highlights the importance of policy support in accelerating the adoption of energy-efficient technologies.

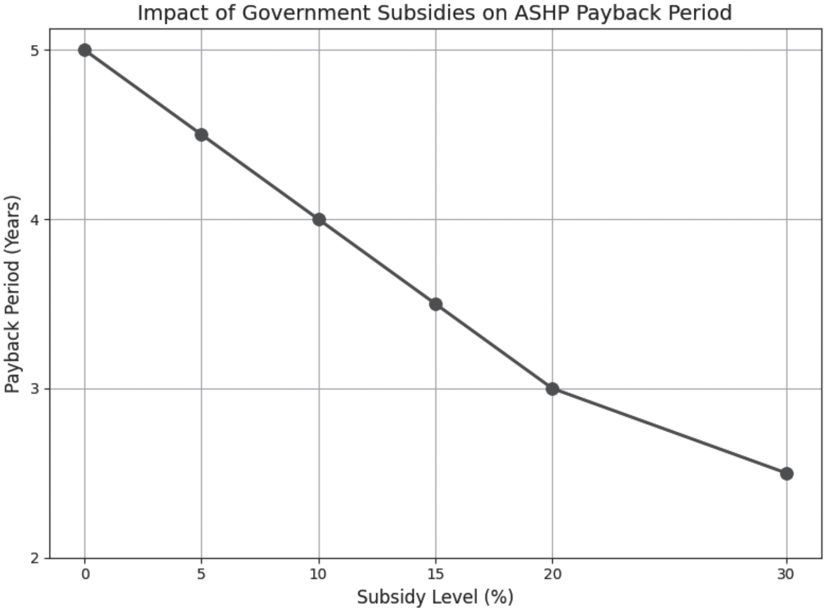

Fig 5. Impact of government subsidies on ASHP payback periods.

As shown in Figure 5, the payback period for the Air Source Heat Pump (ASHP) system is inversely related to the level of government subsidies. Initially, with no subsidy, the payback period is approximately 5 years. However, as the subsidy increases, the payback period decreases significantly. For example, at a 30% subsidy level, the payback period is reduced to just over 2 years. This highlights the critical role that subsidies play in making ASHP systems a more attractive investment for greenhouse operations, facilitating faster returns on investment and promoting wider adoption of energy-efficient technologies.

The sensitivity analysis performed also indicated that ASHP systems are more economically viable in regions with volatile energy prices. In particular, if coal and electricity prices were to rise by 10-20%, the financial attractiveness of ASHP systems would increase due to their higher efficiency. Conversely, a reduction in natural gas prices could potentially slow the adoption of ASHPs, as lower gas prices might make conventional heating systems more cost-competitive. Table 2 shows the effect of energy price fluctuations on the payback period of ASHPs.

Table 2. Impact of energy price fluctuations on the payback period for ASHP systems.

Energy Price Change	Payback Period (Years)
No Change (Baseline)	5
Increase of 10%	4
Increase of 20%	3
Decrease in Gas Price	6

As shown in Table 2, fluctuations in energy prices have a significant impact on the payback period for Air Source Heat Pump (ASHP) systems. Under baseline conditions, the payback period is 5 years. However, if the energy price increases by 10%, the payback period decreases to 4 years, and with a 20% increase, the payback period further reduces to 3 years. Conversely, a decrease in gas prices results in an increase in the payback period to 6 years. These variations highlight how energy price dynamics can influence the financial feasibility and attractiveness of ASHP systems, with higher energy prices accelerating the recovery of the initial investment.

3. Environmental Impact

The environmental benefits of ASHP adoption were also substantial, contributing to significant reductions in carbon emissions. By replacing coal-fired heating systems, the greenhouse gas emissions were reduced by approximately 60%. This reduction aligns with national goals to cut CO2 emissions and transition to more sustainable energy solutions. Furthermore, the use of ASHPs reduces the reliance on non-renewable energy sources such as coal and natural gas, supporting the broader objective of promoting renewable energy and sustainability in agriculture.

The lower carbon footprint of ASHP systems was verified through emissions monitoring conducted at several greenhouse sites. Figure 2 illustrates the comparison of CO2 emissions between ASHP systems and traditional coal-fired heating systems. As shown, the adoption of ASHPs results in a significant reduction in emissions, further cementing their role in helping Shiling Town meet its environmental and sustainability goals.

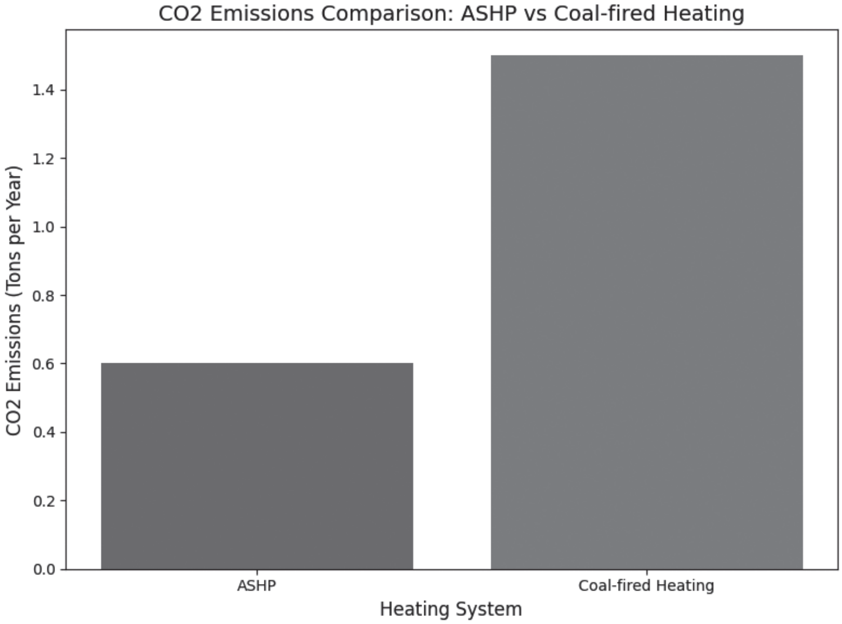

Fig 6. CO2 emissions comparison between ASHP systems and traditional coal-fired heating systems.

As shown in Figure 6, the comparison of CO_2 emissions between ASHP (Air Source Heat Pump) systems and traditional coal-fired heating systems highlights a significant environmental advantage for ASHP. The CO_2 emissions from ASHP systems are considerably lower, at just under 0.6 tons per year, while coal-fired heating systems emit over 1.4 tons of CO_2 annually. This stark difference underscores the environmental benefits of switching to ASHP systems, which offer a much cleaner alternative to conventional fossil-fuel-based heating methods, contributing to reduced carbon footprints in greenhouse operations.

In addition to reducing greenhouse gas emissions, ASHP systems contribute to the reduction of air pollutants commonly associated with coal heating, such as sulfur dioxide (SO2) and nitrogen oxides (NOx). This shift to cleaner energy sources not only improves air quality but also benefits the health of local communities, making ASHP technology a sustainable option both economically and environmentally.

4. Overall Sustainability and Future Prospects

The integration of ASHP technology into Shiling Town's greenhouse sector has shown significant promise in terms of energy efficiency, cost savings, and environmental sustainability. With the continued support of government policies and incentives, ASHPs have the potential to replace traditional, less-efficient heating systems across a larger number of greenhouses, contributing to broader sustainability goals.

Further research is needed to assess the long-term durability and maintenance requirements of ASHP systems in Shiling Town's specific climate and operational conditions. Additionally, expanding the pilot programs and exploring more granular data on energy consumption across various greenhouse sizes could provide deeper insights into optimizing ASHP adoption in the region.

V. Conclusion

This study demonstrates that Air Source Heat Pumps (ASHPs) represent a promising technological solution for enhancing energy efficiency and reducing operational costs in multi-span greenhouses. Despite the higher initial investment required for ASHP systems, the long-term financial benefits, including substantial savings on energy consumption, make them an economically viable option, particularly in regions with supportive government subsidies and rising energy prices. The environmental advantages of ASHPs, notably the significant reduction in CO2 emissions, further reinforce their potential as a key component of a sustainable agricultural strategy.

To promote broader adoption of ASHPs, it is crucial for the government to strengthen its subsidy programs, provide targeted financial incentives, and offer enhanced technical support to greenhouse operators. These measures would address the initial cost barriers and alleviate concerns regarding system maintenance, thereby facilitating the widespread implementation of ASHPs in facility-based agriculture. Such efforts would not only improve the economic feasibility of ASHP adoption but also contribute to the long-term sustainability of agricultural practices in the region.

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